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New limits on the orbital parameters of 1E 1048.1–5937 and 1E 2259+586 from RossiXTE observations

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ABSTRACT

We report on two RossiXTE observations of the anomalous X–ray pulsars 1E 1048.1–5937 and 1E 2259+586. Both sources have continued their almost constant spin-down during 1995/96. We carried out a search for orbital Doppler shifts, in their observed spin frequencies, deriving stringent limits on the projected semi-axis. Unless these systems have unlikely small inclinations, main sequence companions can be excluded. If 1E 1048.1–5937 and 1E 2259+586 are indeed binary systems, their companion stars must be either white dwarfs, or helium-burning stars with M $\lesssim 0.8\ M_{\odot}$, possibly underfilling their Roche lobe.

Key words: Pulsar: individual: (1E 1048.1–5937) - (1E 2259+586) – binaries: close – X–rays: stars.

1 INTRODUCTION

The two sources considered in this article belong to a small group of X–ray pulsars, with periods in the $\sim 5-10$ s range, that have recently attracted much interest owing to their peculiar properties (Mereghetti & Stella 1995). In particular, the lack of bright optical counterparts implies that these neutron stars are not accreting from massive companions, contrary to the great majority of known X–ray pulsars. Other characteristics that distinguish them from the more common pulsars in High Mass X–ray Binaries (HMXRBs) include very soft spectra, X–ray luminosities of the order of $10^{35}-10^{36}$ erg s^{-1}, little long term variability, and relatively stable spin period evolution (see Stella et al. 1997 for a recent review). In the following we will refer to these systems as Anomalous X–ray Pulsars (AXP).

The simplest interpretation for the AXP is that of Low Mass X–ray Binaries (LMXRBs) characterized by lower luminosity and higher magnetic field ($B \sim 10^{11}$ G) than the classical, non-pulsating LMXRBs (Mereghetti & Stella 1995). In this scenario, the observed period distribution, significantly different from that of HMXRB pulsars (which spans from 69 ms to 25 min), can be explained assuming that the neutron stars in AXP are rotating at (or very close to) their equilibrium periods.

However, the absence of orbital motion signatures, such as periodic delays of the pulse arrival times or periodic flux modulations, led also to non standard interpretations based on single stars (e.g. Paczyński 1990; Thompson & Duncan 1993; Corbet et al. 1995; Heyl & Hernquist 1997). Recently it has been proposed that the AXP are the descendant of Thorne-Zytkow objects and consist of isolated neutron stars fed by a residual accretion disk (van Paradijs et al. 1995; Ghosh et al. 1997).

Here we report the results of RossiXTE observations of two AXP: 1E 1048.1–5937, serendipitously discovered with the Einstein Satellite during observations of the Carina nebula (Seward, Charles & Smale 1986), and 1E 2259+586, located at the center of the radio/X–ray supernova remnant G109.1-1.0 (Fahlman & Gregory 1981). Since both sources have not been optically identified so far (Mereghetti, Caraveo & Bignami 1992; Coe & Jones 1992), X–ray observations are the only available tool to assess their binary nature. The main objective of our observations was a search for orbital motions through the detection of Doppler delays in the pulse arrival times. Though such a search gave negative results, the newly derived upper limits provide strong constraints on the possible companion stars for these two AXP.

2 SEARCH FOR ORBITAL MOTION

The observations of 1E 1048.1–5937 and 1E 2259+586 were performed with the RossiXTE satellite (Bradt et al. 1993) from 1996 July 29 22:44 UT to 31 11:30 UT (net exposure

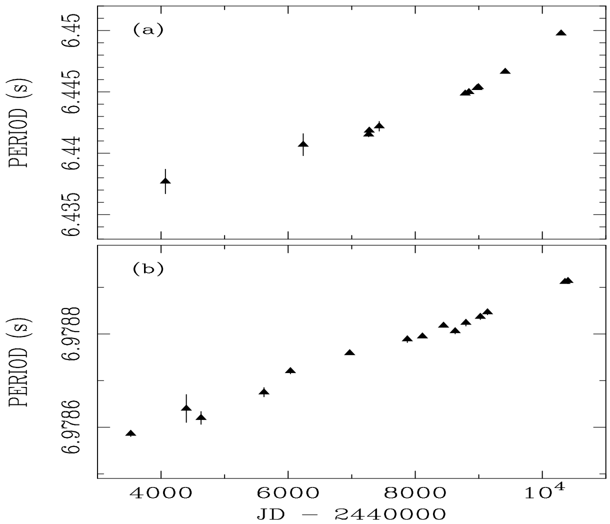

Figure 1. Long term period evolution of 1E 1048.1–5937 (a) and 1E 2259+586 (b).

~86 ks) and from 1996 September 29 15:40 UT to 30 3:05 UT (~77 ks), respectively. The results presented here are based on data collected with the Proportional Counter Array (PCA, Jahoda et al. 1996). The PCA instrument consists of an array of 5 proportional counters operating in the 2–60 keV energy range, with a total effective area of approximately 7000 cm^2 and a field of view, defined by passive collimators, of $\sim 1^\circ$ FWHM. Most of our analysis is based on data collected by the on board electronics in the so called "Good Xenon" operating mode. This provides the time of arrival and the pulse height of each count. In order to reduce the background, only the counts detected in the first Xenon layer of each counter were used.

For each source we determined the spin period with a standard folding technique, after converting to the Solar System barycenter the times of arrival of the counts. We obtained the values $P = 6.449769 \pm 0.000004$ s for 1E 1048.1–5937 and $P = 6.978912 \pm 0.000003$ s for 1E 2259+586. The corresponding light curves are similar to those previously observed from these sources with other satellites. Our period values show that both sources have continued their secular spin-down during 1995/96 (see Fig. 1). The spin period of 1E 2259+586 is smaller than predicted from a linear extrapolation of the last measurements obtained with ROSAT and ASCA. The opposite situation occurs for 1E 1048.1–5937, the spin-down rate of which has further increased.

In the search for orbital Doppler modulations in 1E 1048.1–5937, we considered 1200 trial orbital periods between ~200 s and $\sim 1.3 \times 10^5$ s oversampling the Fourier resolution dictated by the time span of the observation by a factor 2. For each trial period, we computed 8 light curves, folded at the spin period value, corresponding to different intervals of the orbital phase. Particular care was devoted to clean the data from intervals with anomalously high background and to properly take into account the effective exposure of every phase bin. The resulting light curves were cross-correlated with the template one, obtained using all the data, and the peaks in the cross-correlation curves were then fitted with a Gaussian. The Gaussian centroids provide a measurement of possible time delays. To search for the sinusoidal modulation expected in the 8 delays in the case of a circular orbit, we computed their Fourier amplitudes. These are shown in Fig. 2a and 2b as a function of the trial orbital period. As expected, the squared Fourier amplitudes are distributed according to a χ^2 with 2 degrees of freedom. The presence of an orbital modulation would be revealed by a peak exceeding the threshold indicated by the dashed line (corresponding to a 99% confidence level). No significant peaks were found and, following van der Klis (1989), we derive an upper limit of $a_x \sin i < 0.06$ lt-s (99 % c.l.).

The same procedure was applied to 1E 2259+586, for 1200 periods between ~ 194 s and $\sim 1.2 \times 10^5$ s (see Fig. 2c and 2d). Also in this case no significant orbital modulations were found, with an upper limit of $a_x \sin i < 0.03$ lt-s.

Finally, we searched for a periodic modulation in the source light curves by means of a Fourier analysis, without finding any statistically significant periodicity. Using the method of Groth (1975) and Vaughan et al. (1994), modified as described in Israel & Stella (1996), we derived the following 3 σ upper limits on the flux pulsed fraction for the two sources: 2% for periods shorter than 1000 s, ~6% for periods between 1000 s and one hour, and from ~6% to ~20% for increasing period values up to ~5 hours. For comparison, 4U 1820–303, with an orbital period of 11 min, has a peak to peak modulation of 3% (Stella, Priedhorsky & White 1987).

3 DISCUSSION

Previous observations of 1E 1048.1–5937 with the GINGA satellite (Corbet & Day 1990) yielded an upper limit of $a_x \sin i < 0.6$ lt-s for orbital periods between 100 and 1100 s. The source was reobserved with ROSAT in 1992/93 (Mereghetti 1995), with ASCA in 1994 (Corbet & Mihara 1996), and recently with BeppoSAX (Oosterbroek et al. 1997). These observations confirmed the long term spin-down at a rate of $\sim 9 \times 10^{-4}$ s yr^{-1}, but did not allow more sensitive searches for orbital modulations. Our RossiXTE observation has provided an upper limit on $a_x \sin i$ one order of magnitude smaller than the previous value and applicable to a wider range of possible orbital periods. Also in the case of 1E 2259+586 our limits are stronger than the previous value of $a_x \sin i < 0.08$ lt-s for $1000 < P_{orb} < 10000$ s derived with GINGA (Koyama et al. 1989).

In Fig. 3 the new limits on the orbital parameters are plotted for representative values of the unknown inclination angle. Our results significantly reduce the allowed parameter space with respect to the previous limits, setting strong constraints on the nature of the possible companion stars of these pulsars.

The evolution of LMXRBs with orbital periods as short as those considered here ($\lesssim$ few hours), is mainly driven by angular momentum losses due to gravitational radiation. In this case, and with the usual assumption of conservative mass transfer, a well defined relation between the mass M_c of a companion filling the Roche-lobe and the orbital period has to be satisfied (see, e.g., Verbunt & van den Heuvel 1995). This relation depends on the nature of the companion star and has been reported on Fig. 3 for three different cases corresponding to a main sequence star, a helium burning star, and a hydrogen depleted, fully degenerate white dwarf.

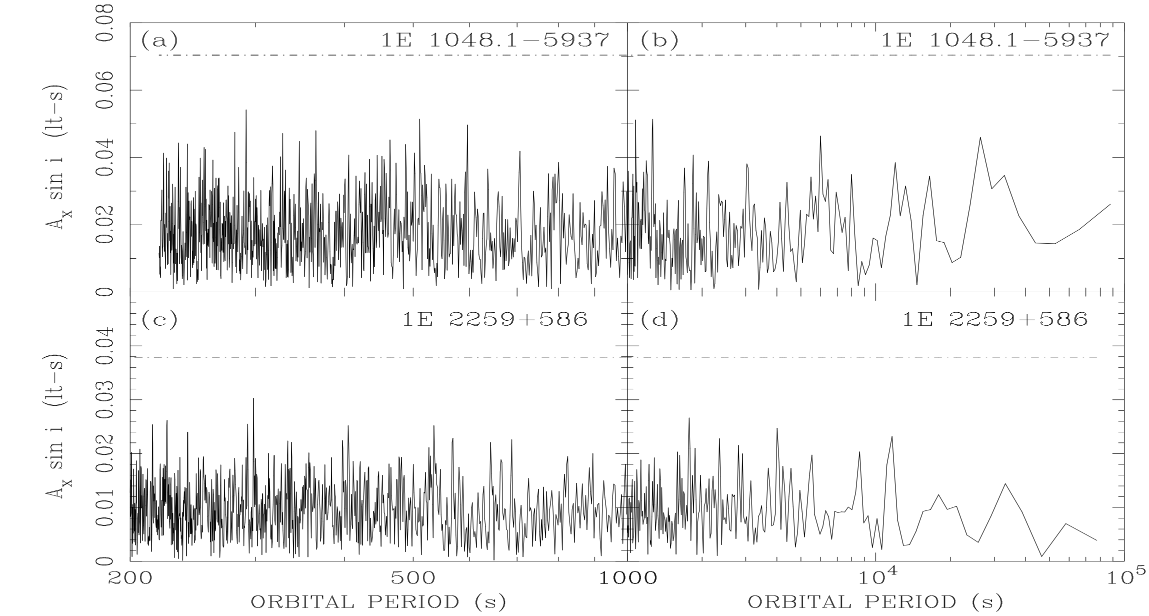

Figure 2. Results of a search for orbital Doppler delays for 1E 1048.1–5937 (a,b) and 1E 2259+586 (c,d). The dashed lines indicate the threshold values on $a_x \sin i$ corresponding to detections at the 99% confidence level. For each source 1200 trial orbital periods between ~ 200 s and ~ 1 d have been searched.

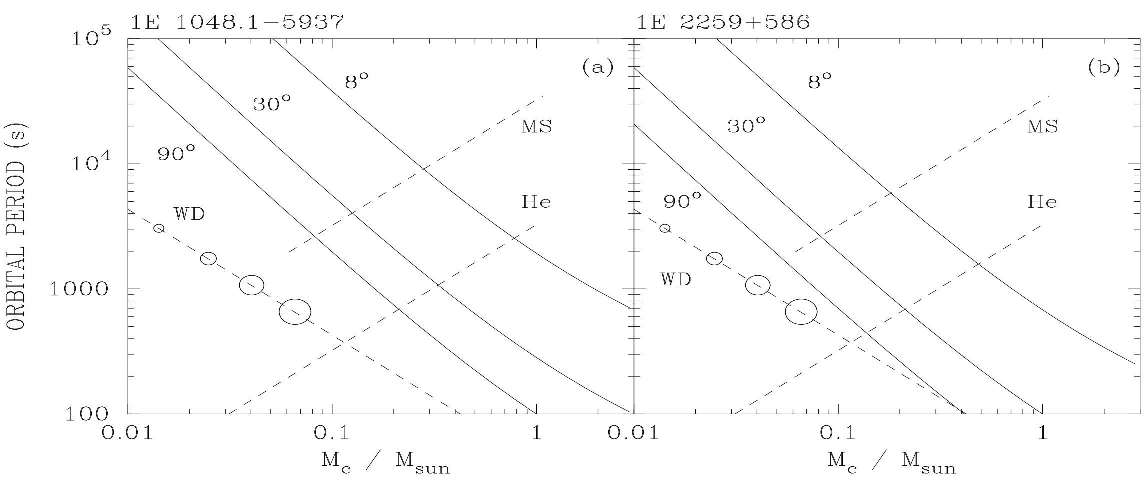

Figure 3. Constraints on the companion mass and orbital period for 1E 1048.1–5937 (a) and 1E 2259+586 (b). The three lines refer to orbit inclinations of 90°, 30° and 8°. A neutron star mass of 1.4 $M_\odot$ has been assumed. Regions above the full lines are excluded by the limits on $a_x \sin i$. The dashed lines indicate the orbital period at which stars of different type fill their Roche lobe for a given mass (see Discussion). The four circles of increasing size correspond to values of $\dot{M} = 10^{-11}, 10^{-10}, 10^{-9}, 10^{-8}$ $M_\odot$ year^{-1}.

3.1 A main sequence companion

The maximum mass of a hydrogen main sequence companion filling the Roche lobe is limited to ~ 0.1 $M_\odot$ for inclinations greater than 30°. Only in the case of a very small inclination, larger masses would be compatible with our limits on $a_x \sin i$. For example, if $i = 8°$ the companion of 1E 1048.1–5937 could be as massive as 0.3 $M_\odot$ (0.2 $M_\odot$ for 1E 2259+586). Note, however, that the chance probability of observing a binary system with an inclination smaller than this is only 1%.

The faintness of the possible optical counterparts of 1E 2259+586 (Coe & Jones 1992) only allows companions of late-K or M spectral type. Since K stars have masses of the order of $0.5 - 1$ $M_\odot$, the presence of such a star can now be considered very unlikely (both in 1E 1048.1–5937 and 1E 2259+586), leaving only a very late-M dwarf as a viable possibility.

3.2 A helium burning companion

Higher masses (up to ~ 0.8 $M_\odot$) are allowed in the case of helium-burning companions filling their Roche lobe.

The measured X–ray fluxes are in the range $(0.6 - 3) \times 10^{-11}$ erg cm^{-2} s^{-1} for 1E 1048.1–5937 (Seward et al. 1986; Corbet & Mihara 1996) and $(2-5) \times 10^{-11}$ erg cm^{-2} s^{-1} for 1E 2259+586 (Iwasawa, Koyama & Halpern 1992; Parmar et al. 1997). Though the distances are uncertain, they are quite well constrained by the size of the Galaxy. In fact both sources are in the galactic plane, and, taking 20 kpc as a reasonable upper limit to their distance, we obtain luminosities $L_x = 4 \times 10^{35}$ $(F/10^{-11}$ erg cm^{-2} s$^{-1})$ $(d/20$ kpc$)^2$ erg s^{-1}.

The corresponding accretion rate ($\dot{M} = 4 \times$

10^{-11} $(F/10^{-11}$ erg cm^{-2} s$^{-1})$ $(d/20$ kpc$)^2$ $M_\odot$ yr^{-1}) is much lower than the value of $\sim 3\times10^{-8}$ $M_\odot$ yr^{-1} expected for Roche lobe overflow accretion from a ~ 0.8 $M_\odot$ helium star (Savonije, Kool & van den Heuvel 1986). Even higher accretion rates would be expected for lower masses and correspondingly shorter orbital periods of a few minutes.

Thus a more likely possibility is that the companion underfills the Roche lobe and accretion is via stellar wind. Such a case has been considered by Angelini et al. (1995) for 4U 1626–67, another source included in the group of AXP (Mereghetti & Stella 1995) despite having some remarkable difference with respect to the other objects. In particular, 4U 1626–67 has an optical identification and a well established orbital period of 42 min (Middleditch et al. 1981; Chakrabarty 1997). Though this led other authors to exclude it from the sample of AXP, it has been proposed (Ghosh et al. 1997) that 4U 1626–67, as well as other short period binaries such as Cyg X-3 (van Kerkwijk et al. 1992) and HD 49798 (Israel et al. 1997), might result from an evolutionary scenario similar to that of AXP, involving a common envelope phase of a progenitor HMXRB.

3.3 A white dwarf companion

It can be seen in Fig. 3 that, due to the different $M_c - P_{orb}$ dependence in the case of accretion from a white dwarf, the limits on $a_x \sin i$ do not constrain the companion mass. A different way to derive some information on the companion is to consider the mass accretion rate expected for different masses and compositions of the white dwarf.

For conservative accretion through Roche lobe overflow, the expected accretion rate depends strongly on the mass of the white dwarf companion. Different values of $\dot{M}$, ranging from 10^{-11} to 10^{-8} $M_\odot$ year^{-1}, have been indicated in Fig. 3 on the white dwarf $M_c - P_{orb}$ relation. Values compatible with the observed luminosity limits can easily be obtained (Savonije et al. 1986). For example, if we use for 1E 2259+586 the distance estimates for the G109.1-1.0 supernova remnant (from 3.6 to 5.6 kpc, Hughes et al. 1984) we derive $\dot{M} \sim 3\times10^{-11}$ $M_\odot$ yr^{-1}. Such a value requires a white dwarf mass of ~ 0.02 $M_\odot$, and the corresponding orbital period would be of the order of 30 min. We note that a white dwarf was discovered among the possible optical counterparts of 1E 2259+586 (star E of Davies & Coe 1991). However, if this star has colours and luminosity of a typical white dwarf, it must be at a distance of $\lesssim 1$ kpc, incompatible with that of the SNR. Thus, if star E, the only object with unusual colours in the field (Coe & Jones 1992), is the counterpart one has to invoke a chance coincidence between 1E 2259+586 and G109.1-1.0 (the alternative possibility that star E be more luminous than a white dwarf runs into problems since, at a distance greater than 3–4 kpc it should also appear more reddened).

4 CONCLUSIONS

The large collecting area of the RossiXTE PCA instruments has allowed a very sensitive search for orbital light propagation delays in the pulsations of 1E 1048.1–5937 and 1E 2259+586. The upper limits on $a_x \sin i$ derived from these observations have greatly reduced the range of possible companion stars and orbital parameters for these sources.

Main sequence companions are now virtually excluded, leaving only either helium-burning stars with M $\lesssim 0.8$ $M_\odot$ or white dwarfs as possible mass donors. Moreover, the low luminosity of these systems excludes orbital periods shorter than $\sim$ 1000 s in the white dwarf case, while in the helium star case it favours mass transfer through a stellar wind.

Though our result supports models for AXP based on isolated neutron stars, a further sensitivity improvement is required to completely rule out binary model (barring the case $i \sim 0^\circ$).

At least in the case of 1E 2259+586, a longer observation with a large collecting area instrument should reveal the presence of an orbital motion or definitely exclude the possibility of a white dwarf companion, independently from its mass.

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